

$B-L$ -symmetric Baryogenesis with Leptonic Quintessence

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Abstract.

We discuss a toy model where baryogenesis and cosmic acceleration are driven by a leptonic quintessence field coupled to the standard model sector via a massive mediating scalar field. It does not require the introduction of $B-L$ -violating interactions below the inflationary scale. Instead, a $B-L$ -asymmetry is stored in the quintessence field, which compensates for the corresponding observed baryon asymmetry.

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1. Introduction

Scalar fields with time-dependent vacuum expectation value are commonly invoked in cosmology, above all to describe the inflationary phase [1] of the early universe, and they are also considered in dynamical dark energy models, called quintessence models [2, 3], aiming to explain the apparent present acceleration [4, 5] of our cosmos. Furthermore, rolling fields are the basis of a number of baryogenesis models [6, 7] and also play an important role in the context of a possible time-variation of fundamental constants over cosmological time-scales [8]. Due to the similarity of the underlying concepts, it is an interesting question whether some of these issues could be related. This has been studied for example for the early- and late time acceleration, called quintessential inflation [9], or for the combination of spontaneous lepto- and baryogenesis with quintessence [10, 11] and quintessential inflation [12].

Complex scalar fields have also been discussed as candidates for dynamical dark energy [13, 14], which offers the possibility that the field carries a $U(1)$ -charge, and thus could itself store a baryon or lepton density [15]. This approach can very well be accommodated within the so-called “baryosymmetric baryogenesis” [16, 17] scenario, where one attempts to explain the overabundance of matter over antimatter without introducing new baryon- (B) or lepton (L) number violating interactions, nevertheless starting with no initial asymmetry. This requires the introduction of an invisible sector, in which an asymmetry is hidden that exactly compensates the one observed in the

baryon (and lepton) sector, thereby circumventing one of the Sakharov conditions [18]. Here we will review a possible realization where the anomaly-free combination $B-L$ is conserved below the inflationary scale, and the invisible sector which compensates for the $B-L$ -asymmetry of the standard model (SM) baryons and leptons is leptonic dark energy following Ref. [15]. For other realizations involving dark matter or neutrinos see e.g. Refs. [16, 19].

2. Toy Model

In this section we address the question how $B-L$ -asymmetries in the dark energy sector, realized by a complex quintessence field charged under $B-L$, and in the SM sector can be created by a dynamical evolution within an underlying $B-L$ -symmetric theory. For this, it is necessary to consider a suitable interaction between both sectors. Direct couplings between the quintessence field and SM fields are commonly investigated for example in the context of time-varying coupling constants and/or -masses [8] or violations of the equivalence principle [3], which leads to strong constraints in the case of a coupling e.g. to photons or nucleons [20, 3, 21]. Here, we discuss a toy model where we assume that direct interactions between the quintessence field ϕ and the SM are sufficiently suppressed, allowing however an indirect interaction mediated by a “mediating field” χ which couples to ϕ and the SM. In the late universe, the χ -interactions should freeze out which means that the massive scalar χ is hidden today and also that the transfer of asymmetry between the quintessence and the SM sector freezes out. Thus, once an asymmetry has been created in each sector in the early universe, it will not be washed out later on. In the specific setup considered here we take the quintessence field to carry lepton number -2 , so that it carries a $B-L$ -density given by

$$n_\phi = -2|\phi|^2\dot{\theta}_\phi \quad (\text{with } \phi \equiv |\phi|e^{i\theta_\phi}), \quad (1)$$

and analogously for the mediating field χ which carries the same lepton number. The effective toy-model Lagrangian for ϕ and χ we consider is

$$\begin{aligned} \mathcal{L} = & \frac{1}{2}(\partial_\mu\phi)^*(\partial^\mu\phi) - V(|\phi|) + \frac{1}{2}(\partial_\mu\chi)^*(\partial^\mu\chi) - \frac{1}{2}\mu_\chi^2|\chi|^2 \\ & - \frac{1}{2}\lambda_1|\phi|^2|\chi|^2 - \frac{1}{4}\lambda_2(\phi^2\chi^{*2} + \text{h.c.}) + \mathcal{L}_{SM}(\chi, \dots), \end{aligned}$$

with dimensionless coupling constants $\lambda_1 > 0$ and $\lambda_2 < \lambda_1$ responsible for the coupling between the quintessence and the mediating field. This Lagrangian has a global $U(1)$ -symmetry under a common phase rotation of ϕ and χ which corresponds to a $B-L$ -symmetric theory. The coupling of the mediating field to the SM encoded in the last contribution should also respect this symmetry. This is compatible e.g. with a Yukawa-like coupling of the form $\mathcal{L}_{SM} \ni -g\chi\bar{\nu}_R^c\nu_R + \text{h.c.}$ to right-handed neutrinos, see Ref. [15] for a more detailed discussion. For the quintessence potential we assume an exponential potential of the form [22, 23, 2, 3] $V(|\phi|) = V_0 (e^{-\xi_1|\phi|/M_{\text{Pl}}} + ke^{-\xi_2|\phi|/M_{\text{Pl}}})$ which leads to tracking of the dominant background component and a crossover towards an accelerating attractor at the present epoch for $\xi_1 \gg 2 \gg \xi_2$ and a suitable choice of k [22]. For the dynamics in the early universe one can safely neglect the second term. Since the vacuum

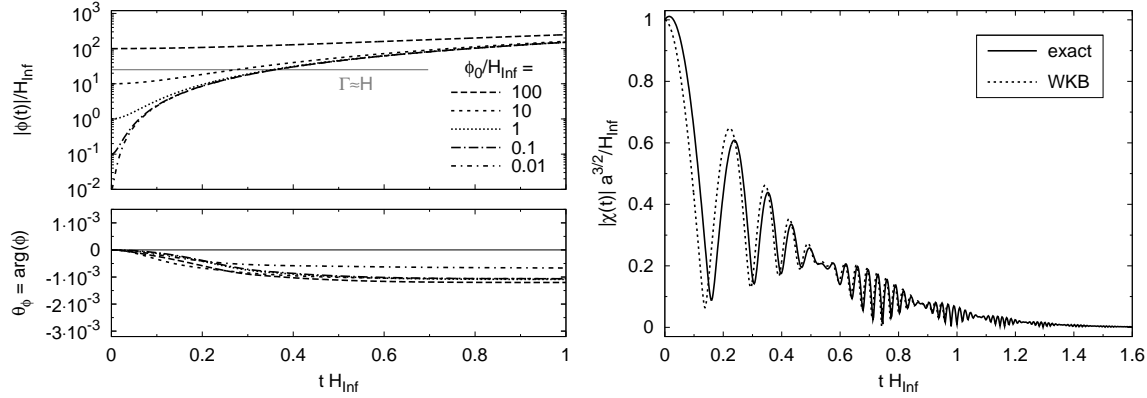


Figure 1. Left: Numerical solution for the absolute value of the quintessence VEV $|\phi|$ (upper) and its complex phase (lower) for various initial conditions ϕ_0 and the choice $\lambda_1 = 1, \lambda_2 = 0.1, V_0/\rho_0 = 10^{-5}, \xi_1 = 7, \chi_0 = H_{\text{Inf}} = 10^{12}\text{GeV}, \alpha_0 = \frac{\pi}{4}, g = 1$ of parameters. **Right:** Numerical and approximate WKB solution for the absolute value of the mediating field VEV $|\chi|$ for the same parameter values despite $\phi_0 = H_{\text{Inf}}$.

expectation value (VEV) of ϕ increases and typically $|\phi| \gtrsim M_{\text{Pl}}$ today, the effective mass $m_\chi^2 \approx \mu_\chi^2 + \lambda_1 |\phi|^2$ of the mediating field gets huge and the field indeed decouples the quintessence and the SM sectors in the late universe. However, before the electroweak phase transition the dynamics of ϕ and χ can lead to a creation of the baryon asymmetry.

3. Creation of a B–L-asymmetry

To study the evolution of the scalar fields ϕ and χ in the early universe, we assume that it is described by a flat FRW metric after the end of inflation with a Hubble parameter $H = H_{\text{Inf}}$ and with VEVs $\phi = \phi_0$ and $\chi = \chi_0 e^{-i\alpha_0}$ inside our Hubble patch which are displaced by a relative angle α_0 in the complex plane. These initial conditions correspond to dynamical CP violation if $\sin(2\alpha_0) \neq 0$, which is necessary for the formation of an asymmetry [24, 17]. Under these conditions, the fields start rotating in the complex plane and thus develop a B – L -density, see eq. (1). This asymmetry is then partially transferred to the SM by the B – L -conserving decay of the χ -field into SM particles, leading to a decay term for the χ -field in the equations of motion [15]

$$\begin{aligned} \ddot{\phi} + 3H\dot{\phi} &= -2\frac{\partial V}{\partial \phi^*} - \lambda_1 |\chi|^2 \phi - \lambda_2 \phi^* \chi^2, \\ \ddot{\chi} + 3H\dot{\chi} + 3\Gamma_{\chi \rightarrow \text{SM}} \dot{\chi} &= -\mu_\chi^2 \chi - \lambda_1 |\phi|^2 \chi - \lambda_2 \chi^* \phi^2, \end{aligned}$$

where $\Gamma_{\chi \rightarrow \text{SM}} = \frac{g^2}{8\pi} m_\chi$ is the decay rate and g^2 stands for the squared sum of the Yukawa couplings corresponding to the relevant decay channels. Provided that the quintessence behaviour is dominated by the exponential and not by the mixing terms (which is roughly the case if $|V'(\phi_0)| \gg \chi_0^2 \phi_0, \chi_0^3$), it will roll to larger field values with only small changes in the radial direction, whereas the χ -field oscillates and decays once $\Gamma_{\chi \rightarrow \text{SM}} \gtrsim H$ (see Fig. 1). Due to the B – L -symmetry, the total B – L -density is conserved, and thus the

asymmetries stored in the different components always add up to the initial value which we assume to be zero after inflation, i.e.

$$n_\phi + n_\chi + n_{\text{SM}} \equiv 0. \quad (2)$$

After the decay of the χ -field, the comoving asymmetry freezes (see left part of Fig. 2) since there is no more exchange between the quintessence and the SM sectors[‡] [15],

$$n_{\text{SM}} a^3 \rightarrow -n_\phi a^3 \rightarrow \text{const} = \int_0^\infty dt a^3 \Gamma_{\chi \rightarrow \text{SM}} \cdot n_\chi \equiv A_\infty, \quad (3)$$

and thus the B – L -asymmetry in the SM is exactly compensated by the B – L -asymmetry stored in the quintessence field. The final yield of the B – L -asymmetry

$$n_{\text{SM}}/s = D \cdot \kappa \equiv D \cdot \frac{-A_\infty}{3.2\rho_0^{3/4}} \propto A_\infty \quad (4)$$

(where $\rho_0 \equiv 3H_{\text{Inf}}^2 M_{\text{Pl}}^2$) can actually be calculated either numerically or, for a restricted parameter range, analytically via the integral in eq. (3) using an approximate WKB solution for $\chi(t)$ [15] (see Fig. 1 and Fig. 2),

$$\kappa \approx -\frac{\mathcal{N}}{2} \sin(2\alpha_0) \left(\frac{\chi_0}{H_{\text{Inf}}} \right)^2 \cdot \begin{cases} 3.6 \cdot 10^{-10} \frac{\phi_0}{10^{13} \text{GeV}} \left(\frac{H_{\text{Inf}}}{10^{12} \text{GeV}} \right)^{\frac{1}{2}} & \text{if } \phi_0^3 \gg \chi_0^2 \phi_0, |V'(\phi_0)| \\ 1.7 \cdot 10^{-8} \left(\frac{\xi_1}{7} \frac{V_0}{\rho_0} \right)^{\frac{1}{3}} \left(\frac{H_{\text{Inf}}}{10^{12} \text{GeV}} \right)^{\frac{7}{6}} & \text{if } |V'(\phi_0)| \gg \phi_0^3, \chi_0^3, \end{cases} \quad (5)$$

where $\mathcal{N} \equiv \mathcal{N}(\lambda_1, \lambda_2, g)$ contains the dependence on the coupling constants, with $\mathcal{N} \sim 1$ for $g^2/(8\pi) \sim \lambda_2/\lambda_1 \ll \lambda_1 \sim 1$ [15]. The analytic estimate agrees well with the numerical results (see Fig. 2) inside the respective domains of validity. In the notation of eq. (4) $\kappa \propto A_\infty$ is the contribution which depends on the dynamics of the quintessence and the mediating field, and D is a factor of proportionality which depends on the expansion history of the universe after inflation and can vary in the range $1 \gtrsim D \gtrsim 10^{-6}$ for various models of inflation and re/preheating [15]. Thus, arriving at the observed value[§] $n_{\text{SM}}/s \sim 10^{-10}$ is possible if the asymmetry parameter κ is roughly in the range $10^{-10} \lesssim \kappa \lesssim 10^{-4}$, which is indeed the case for a broad range of values for the initial energy density and VEV of the quintessence field (see right part of Fig. 2).

4. Final Remarks

An important issue in the context of complex quintessence models is to study the stability against the formation of inhomogeneities, which could otherwise lead to the formation of so-called Q-balls [26] and destroy the dark energy properties. Once the

[‡] We set $t \equiv 0$, $a \equiv 1$ at the end of inflation

[§] Note that the B – L -asymmetry and the baryon asymmetry differ by an additional sphaleron factor of order one, see Ref. [25].

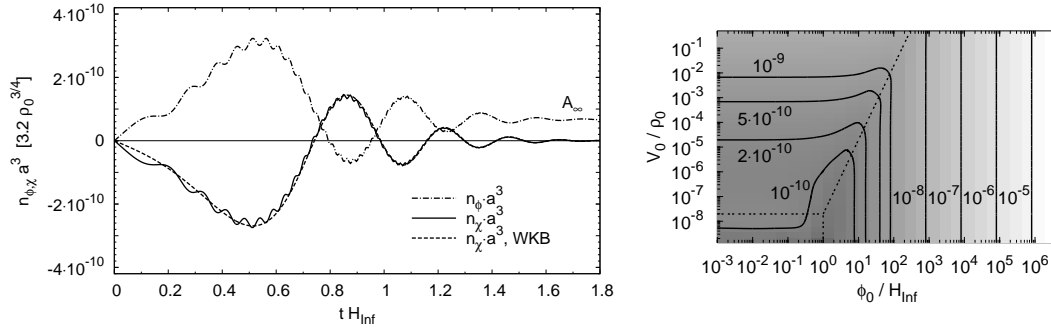


Figure 2. Left: Time-evolution of the comoving asymmetry of the quintessence (dot-dashed) and the mediating (solid) fields for the same parameters as in Fig. 1 despite $g = 0.5$. After an initial phase of oscillations, the χ -field decays and the asymmetry stored in the quintessence field goes to a constant asymptotic value A_{∞} which is of equal amount but opposite sign as the asymmetry created in the SM. The analytic WKB approximation for n_{χ} is also shown (dashed). **Right:** Contour plot of the created asymmetry $\kappa \propto A_{\infty}$. V_0/ρ_0 corresponds to the fraction of quintessence energy density after inflation and ϕ_0 is the initial quintessence VEV. The other parameters are chosen as in Fig. 1. The dashed lines divide the regions where the analytic approximations from eq. (5) are valid.

comoving asymmetry is frozen one can estimate from eq. (1) the phase velocity $\dot{\theta}_{\phi}$ which is necessary to yield an asymmetry $n_{\phi}/s \sim 10^{-10}$,

$$\frac{|\dot{\theta}_{\phi}|}{H} = \frac{|n_{\phi}|}{2H|\phi|^2} \sim 10^{-10} \frac{2\pi^2}{45} g_{*S}(T) \frac{T^3}{2H|\phi|^2} \lesssim 10^{-8} \frac{(HM_{\text{Pl}})^{3/2}}{2H|\phi|^2} \ll 10^{-8}, \quad (6)$$

where we assumed $g_{*S}(T) \sim 100$ and $|\phi| \gtrsim M_{\text{Pl}}$. Thus the field is moving extremely slowly in the radial direction compared to the expansion rate of the universe, which is exactly the opposite limit as was studied for example in the spintessence models [13]. Quantitatively, one can show [27] that there exist no growing modes for linear perturbations in $|\phi|$ and θ_{ϕ} for any wavenumber k provided that $\dot{\theta}_{\phi}^2 < \frac{3H+2\dot{\varphi}/\varphi}{3H+6\dot{\varphi}/\varphi} V''$ (with $\varphi \equiv |\phi|$, $V'' \equiv d^2V/d\varphi^2$). Since the mass $V'' \sim H^2$ of the quintessence field tracks the Hubble scale [28] and since $\dot{\varphi}/\varphi > 0$ this inequality is safely fulfilled once the tracking attractor is joined, and thus there are no hints for instabilities in this regime. For a more detailed analysis including also the early moments of evolution as well as additional particle processes we refer to Ref. [15].

Finally, we want to mention that, since the underlying Lagrangian is B – L -symmetric, it offers a possibility to combine Dirac-neutrinos with baryogenesis aside from the Dirac-leptogenesis mechanism [19]. Note that the lepton-asymmetry in the SM is of opposite sign compared to Dirac-leptogenesis. Furthermore, there is no specific lower bound on the reheating temperature like in thermal leptogenesis [29].

In conclusion, the coupled leptonic quintessence model reviewed here can account for the observed baryon asymmetry of the universe without introducing new B – L -violating interactions below the inflationary scale by storing a lepton asymmetry in the dark energy sector.

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